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Effects of Porosity on CFRP Repair Performance with Aerospace Applications

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Abstract

On-site repairs of carbon fiber reinforced polymer composites, wet layup repairs with heat blanket method play a critical and practical role for the composite defects that occur in production and assembly. The porosity level should be controlled for the repair parts with heat blanket method since the pressure value, which enables ply consolidation, reduce the risk of delamination in the composite layers, is less or zero with the wet layup repaired parts with heat blanket compared to repair parts with autoclave pressure.

In this experimental study, an investigation was conducted regarding the tensile strength change of prepreg structures using wet lay-up repair techniques with heat blanket based on the porosity, with a specific focus on stepped-repaired carbon fiber reinforced polymer laminates.

This work aims to understand the strength and the associated failure mechanisms of on-site repaired woven carbon fiber reinforced polymer laminates through experiments. The Automatic Ultrasonic Pulse Echo Inspection Method was utilized to see whether porosity level of each repaired samples is within allowable design limits for this purpose. Prepreg structure's repairs using wet lay-up produced according to standardized aerospace procedures were tested under uniaxial tension per ASTM 3039D. The relationship between attenuation difference (ΔdB) and tensile fracture values has been explored, with a focus on investigating the associated failure mechanisms. Initially, a 60% strength recovery was observed for repairs with an 8-decibel difference. However, as the decibel difference increased, the strength recovery gradually decreased, ultimately reaching 45.2%.

1. Introduction

Carbon Fiber Reinforced Polymers (CFRP) have found extensive applications in aerospace, automotive, and various other industries due to their high strength-to-weight ratio and corrosion resistance (Das et al., 2020; Pumchusak et al., 2021). The maintenance and repair of CFRP composites are crucial for prolonging the structural integrity and safety of the applications they serve (Li et al., 2018). The strength and service life of composite structures can be adversely affected by environmental factors such as temperature fluctuations and moisture absorption (Budhe et al., 2018). The curing conditions significantly influences the properties of CFRP, impacting attributes such as density, porosity percentage, hardness, tensile strength, impact strength, and wear rates. The reinforcement of carbon fibers (CFs) in polymers leads to substantial improvements in thermal and mechanical properties, which underscores the importance of curing time in optimizing these properties for various applications. Studies have shown that porosity, potentially resulting from partially effective cure cycles, alongside low-energy impact damage, can significantly affect the residual properties of CFRP laminates. The effects of porosity have shown to have controversial results on the residual flexural strength following low-energy impacts (Das et al., 2020). On-site repair, particularly in the aerospace sector, has become a focal point of study to ensure minimal downtime and enhanced operational readiness.

Numerous CFRP components continuously operate under harsh environmental conditions. The high costs of CFRP components, often not in proportion to their lifetime, necessitate effective repair methods. A novel repair procedure suggests using an oxide semiconductor activated by ultraviolet (UV) irradiation to locally depolymerize the thermoset matrix of damaged CFRP components. This approach enables the removal of harmed fibers from the laminate in the damaged area, followed by the application of a load-adjusted tailored fiber reinforcement patch, consolidated by local thermoset re-infiltration, thus achieving repaired CFRP structures with reduced mechanics and an approximately original surface (Rabe et al., 2021).

Further, the mechanical properties of CFRP are significantly influenced by various factors including the volume/weight fraction of reinforcement, L/D ratio of fibers, orientation angles, and curing temperature. These factors underscore the adaptability of CFRP as one of the most advanced and adaptable engineering materials (Mehar et al., 2015). In the realm of underwater and above water repair, the use of Fiber Reinforced Polymer (FRP) composite materials for repairing structural steel tubular members in the offshore industry has emerged as a viable solution. However, more detailed studies on long-term performance and cyclic behavior of composite repaired members are yet to be conducted (George et al., 2021). Structural health monitoring plays a pivotal role in CFRP structural bonded repair. The rising interest in polymer-based composites is attributed to their enhanced mechanical properties and weight-saving advantages compared to conventional structural alloys (Sánchez-Romate et al., 2021). Moreover, CFRP matrix composite overwrap repair systems have been introduced as alternative repair systems for steel pipelines. Through finite element (FE) analysis, the mechanical behavior of damaged steel pipelines with CFRP repair was evaluated, considering different repair strategies such as wrap repair and patch repair (Chen et al., 2021). There are two main methods commonly used for composite repair are autoclave curing and heat blanket curing (Kubit et al., 2020). Autoclave curing has long been the standard method for composite repair due to its ability to provide uniform temperature and pressure throughout the repair process (Choupani & Torun, 2022).

Autoclave curing, although highly effective, may not always be feasible in certain situations, such as on-site repairs or in remote locations where access to an autoclave is limited. In such cases, heat blanket curing becomes the preferred option due to its portability and ease of setup. However, it is important to note that there are factors that need to be carefully considered when opting for heat blanket curing.

One of the challenges associated with heat blanket curing is the porosity effect, which can lead to variations in material properties. This is due to the uneven distribution of heat and pressure that can occur during the curing process. The use of heat blankets can result in localized high temperatures and pressure gradients, which can lead to insufficient consolidation of the composite materials. Porosity, or the presence of voids and air pockets within the composite, can significantly impact the strength and integrity of the repaired area.

The combination of light curing, heat curing, and pressure curing improved the mechanical properties of resin composites (Karaarslan et al., 2013). Furthermore, the use of light curing in conjunction with heat and pressure curing has been shown to enhance the mechanical properties of resin composites. Previous studies by Silva et al. demonstrated that the utilization of light curing, in addition to heat and pressure curing, resulted in improved mechanical properties of resin composites (Da Silva et al., 2007). Adeodu et al. found a direct relationship between the tensile strength of composites and the weight percentage of fillers used in post-curing methods (Adeodu, 2015).

2. Experimental Work

The production and maintenance processes for composite laminates adhere to established industry standards commonly employed in the creation and repair of composite materials utilized in aircraft. These laminates were constructed using a specific type of carbon/epoxy fabric known as M21/AS4C/40RC/T2/285/6K with a cure coat thickness of 0.285 mm. The fabric was arranged in a 2×2 twill pattern with orientations of 45/0/45/0/45/0/45. This fabrication procedure resulted in the generation of 11 composite samples, each measuring 250×25×2 mm in size.

These samples were manufactured under precise conditions, involving a temperature of 180°C and a constant pressure of 7 bar, over a duration of 9 hours (Hexcel, 2023). All these manufacturing steps adhered to the manufacturer's provided specifications to ensure the quality and integrity of the composite laminates. This meticulous approach is essential in meeting the stringent requirements and safety standards expected in the aerospace industry, where the reliability of composite materials is of paramount importance in ensuring the structural integrity of aircraft components. Specimen plies can be seen in Fig. 1.

The dimensions and configuration of the test specimens were prepared in strict accordance with the specifications outlined in the ASTM Tensile Test Standard for Polymer Matrix Composites (D3039/3039 M) (ASTM, n.d.). A section measuring 20 mm × 20 mm × 1.7 mm was carefully extracted from the central region of each sample using sandpaper with a grit of 120° or finer.

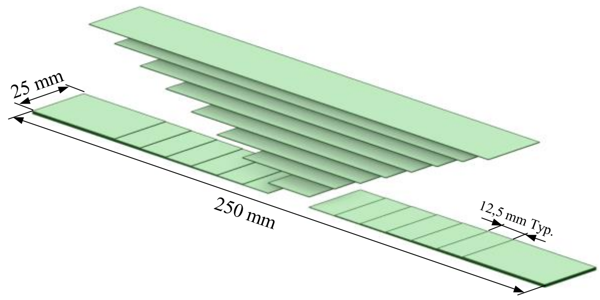

Figure 1. Exploded view of the composite specimen.

The carbon plies were opened with 12.5 mm overlaps from the bottom to the top region and then the removed plies were re-laid with the same orientation. The curing process was conducted at 66 +/- 2 degrees Celsius for 1 hour, following the Hysol EA9396 procedures. After curing, any excess resin was sanded and smoothed to prepare the specimen for testing.

The carbon plies were initially separated with 12.5 mm overlaps, extending from the lowermost section to the upper region. Subsequently, the plies that had been removed were repositioned with the same orientation. The curing process was performed in strict accordance with the Hysol EA9396 procedure, maintaining a temperature of 66 +/- 2 degrees Celsius for a duration of 1 hour. Following the curing step, any surplus resin was carefully sanded and smoothed to render the specimen ready for testing.

The curing procedures were meticulously executed in strict accordance with the guidelines provided by the resin manufacturer. Subsequent to the curing process, five distinct sample types were prepared, each incorporating an additional ply. These plies were applied in a wet state, featuring 12.5 mm overlaps, utilizing parent prepreg structure to perform repair.

Furthermore, the samples were created by strategically adding an extra ply on the tool side. Those samples crafted using the wet method were subjected to a curing process within a vacuum environment at 650 mmHg, employing a heat blanket (HEATCON) system (see Fig. 2.).

Figure 2. Bagging and curing process with the heat blanket (HEATCON) (HEATCON, 2023).

For the wet layup method, the application involved the use of Hexforce G0904 D 1070 TCT plain weave dry carbon fabric, which was expertly impregnated with Hysol EA 9396 resin (Ahn & Springer, 2000). This comprehensive approach adhered to stringent technical specifications, ensuring the precision and quality of the resultant composite samples. The characteristics of the carbon and resin applied through the wet layup method have been comprehensively documented in Tables 1. and 2. In this process, additional plies were oriented at 45 degrees, and plies with the same alignment as the top ply were thoughtfully selected. Following the completion of the repair and curing cycle for the prepared samples, a meticulous evaluation was carried out with the aid of Manual Ultrasonic Pulse Echo Inspection (MUPE). This inspection aimed to identify defects, such as delamination and debonding, ensuring the integrity of the samples. Furthermore, the assessment extended to the examination of porosity within the samples, employing the MATEC ultrasonic tester, based in MA, USA.

Table 1. Mechanical properties of Hexforce G0904 plain weave dry carbon fabric impregnated with Hysol EA 9396 adhesive, with a 1/3 weight ratio and M21 / AS4C impregnated material (Ahn & Springer, 1998; Hexcel, 2023; Sonat, 2021; Sonat & Özerinç, 2021).

Property	Symbol	Hexforce G0904	M21 / AS4C
Elastic Modulus (GPa)	E_{11}	49.6	61.0
	E_{22}	49.6	61.0
	E_{33}	8.0	8.9
Shear Modulus (GPa)	G_{12}	3.3	4.2
	G_{13}, G_{23}	2.8	3.8
Tensile Strength (MPa)	X_t	517	930
	Y_t	517	940
Shear Strength (MPa)	S_{12}	60	96
	S_{13}, S_{23}	34	64
Poisson's Ratio	ν_{12}	0.045	0.05
	ν_{13}, ν_{23}	0.28	0.3

The Automatic Ultrasonic Transition Method (AUTT) was utilized for this purpose. Maintaining porosity values within a specified 6 dB attenuation difference (ΔdB) was the criterion for acceptance of the samples for testing. While laminated, non-resinous areas of the samples exhibited the desired 6 dB attenuation difference, the repaired regions showed a range of 5-20 dB attenuation difference, primarily due to the presence of porosity. It's crucial to emphasize the significance of the Nondestructive Inspection application, as it aims to detect and assess porosity and defects within the laminate. The existence of porosity in the resin can indeed influence the test results in terms of the structural integrity of the composite material.

Table 2. Mechanical Properties of the adhesives (Henkel, 2023; J et al., 1997; Solvay, 2023; Sonat, 2021; Sonat & Özerinç, 2021).

Property	Symbol	FM-300K	HYSOL EA 9396
Tensile Modulus (GPa)	E	3.12	2.7
Shear Modulus (GPa)	G	0.9	0.7
Tensile Strength (MPa)	t_n^0	72	55
Shear Strength (MPa)	t_s^0, t_t^0	42	26
Tensile Stiffness (N/mm^3)	K_n	15,600	10^6
Shear Stiffness (N/mm^3)	K_s, K_t	4500	10^6
Toughness in Tension (N/mm)	G_{IC}	1.1	0.3
Toughness in Shear (N/mm)	G_{IIC}, G_{IIIC}	4.8	0.5

Following the comprehensive inspection process, the next step involved subjecting the samples to plain tension tests, which were conducted in strict accordance with ASTM 3039 guidelines. These tests were carried out using the Instron 8852 Tensile Testing Machine, headquartered in MA, USA. The test setup is illustrated in Fig. 3., providing a visual representation of the experimental configuration. To ensure the precision of stress and strain measurements, a clip-on extensometer was thoughtfully employed. This advanced measurement device played a crucial role in enhancing the accuracy of the results obtained during the testing process. By adhering to these standardized testing procedures and utilizing state-of-the-art equipment, the mechanical properties of the samples were effectively evaluated, shedding light on their structural integrity and performance characteristics.

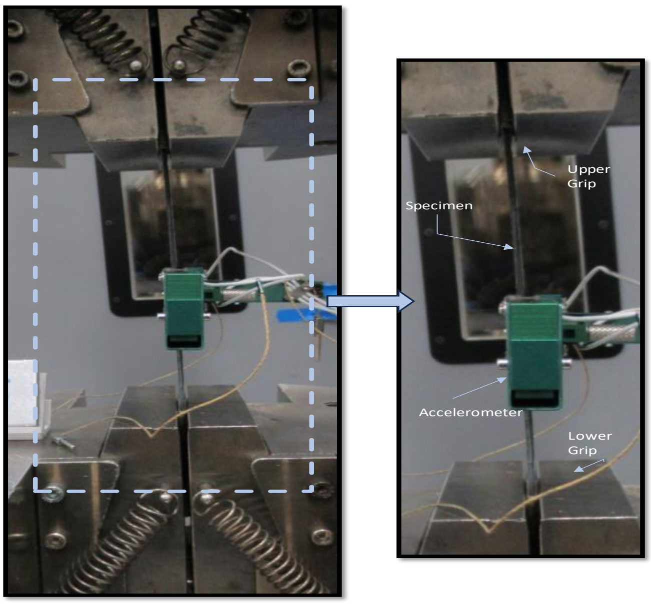

Figure 3. Test configuration.

3. Data Collection and Analysis

In Fig. 4., it can be observed representative tensile force-displacement curves obtained from our experimental tests, focusing on both the repaired and intact specimens. These curves are based on crosshead displacement measurements.

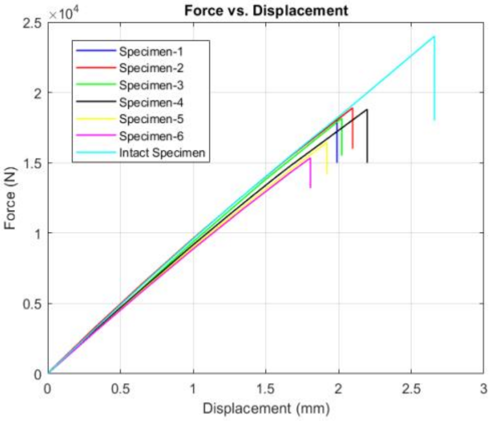

Figure 4. Force and displacement test results of the specimens.

The intact specimen displays a consistently linear elastic response, reflecting its structural integrity. In contrast, the repaired specimens initially exhibit a response that is quite similar to the intact one, with comparable stiffness up to approximately 1.8 mm of displacement. However, as the displacement increases further, we observe a notable decrease in the load-displacement slope for the repaired specimens. This phenomenon is followed by an abrupt and distinct ultimate failure point, without any substantial plastic deformation in any of the specimens.

It's worth noting that, it is observed the distinct sound of fiber breakage, confirming the observations. The observed deviation in slope for the repaired specimens strongly implies a cohesive failure within the adhesive material employed in the repair process. This outcome underscores the significance of adhesive quality and compatibility when reinforcing composite structures, as the reduction in slope indicates a potential weakness in the bond between the repair material and the parent composite structure.

The failure mechanism becomes evident that the impact of porosity on the overall structural integrity cannot be underestimated (see Table 3.). The presence of porosity, a minute difference in sound density within 2-3 decibels, can compromise the load-bearing capacity of the repaired area. In the case of wet lay-up repaired specimens, the intricate interplay between the repair material and the original laminate is accentuated, as any porosity within the repair material can exacerbate the degradation of mechanical properties. Additionally, in the earlier stages of the tests, it is noticed minor deviations from perfect linearity. These deviations can be attributed to slight slippage occurring in the grips of the testing machine, an aspect that is taken into account during the analysis.

4. Results and Discussion

The key parameters assessed are the number of specimens tested, attenuation difference, maximum tensile strength, and the recovery rate. Table 3. provides a summary of the results obtained from our tensile testing, which included various specimens. Specimens tested column indicates the number of individual specimens of each type that were subjected to tensile testing. There was a single specimen for Specimen-1, Specimen-2, Specimen-3, and so on. However, Specimen-7 had a total of six specimens tested to obtain exact structure allowable. Attenuation difference signifies the variation in tensile strength across the different specimens. A lower attenuation difference for repaired specimen suggests that the specimens had more consistent intact specimen’s tensile strength results. The values range from 9.2 to 16 for the different specimen types. Attenuation differences signify variations in tensile strength across different specimen types, and our findings suggest that substantial differences have a noteworthy impact on the material's overall strength. These attenuation differences are not uniform across the entire structure; instead, they are localized within specific regions. To fully comprehend their implications, it is imperative to conduct a detailed examination of the density of these localities. These localized variations have the potential to act as points of weakness within the structure, which necessitates a thorough investigation to understand their origin and impact.

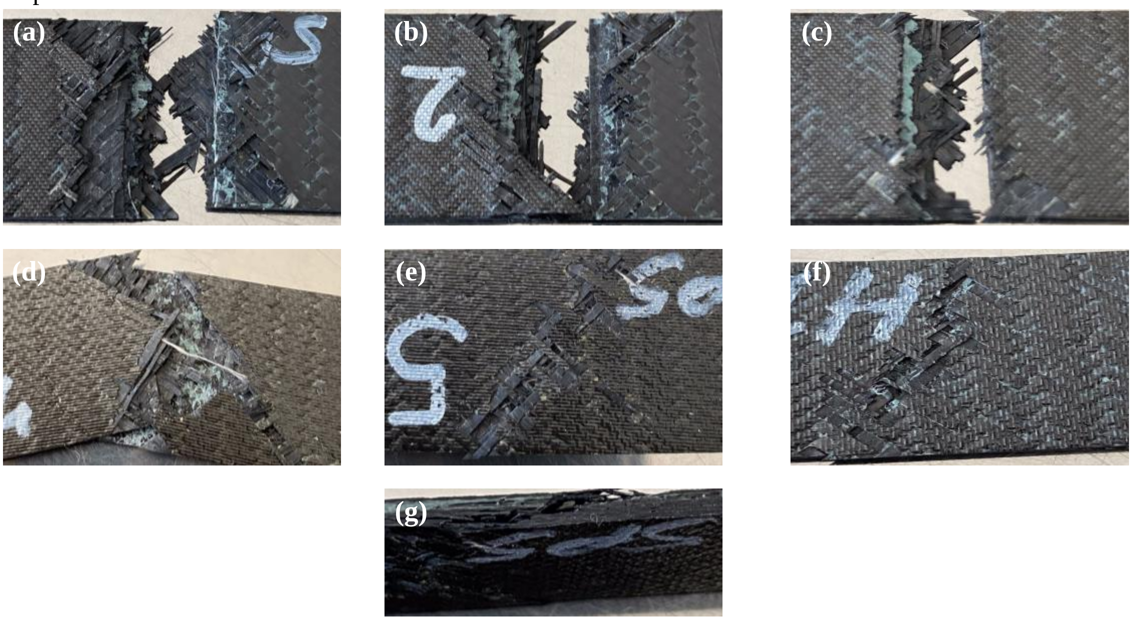

Figure 5. Fracture behavior of the specimens. (a) Specimen-1, (b) Specimen-2. (c) Specimen-3, (d) Specimen-4, (e) Specimen-5. (f) Specimen-6, (g) Side 5-6.

In Fig. 5., as observed, Specimens 1, 2, and 3 have exhibited the same fracture behavior. While both cohesive and adhesive failure mechanisms were observed in these specimens, the porosity level in the repaired area, which constitutes 80% of the specimen, resulted in the desired fracture mechanism. However, the recovery strength of the specimen remained at 60%. When compared with previous research, where a recovery rate of 80% was achieved without the addition of an extra ply, a 20% reduction in the recovery rate is evident (Sonat et al., 2023).

By assessing attenuation differences, we gain insights into the porosity values of CFRP composites. Porosity refers to the presence of voids or tiny air pockets within the composite material. These voids weaken the structural integrity of the material. When stress is applied, these voids can act as stress concentration points, making the material more susceptible to failure. The presence of voids means that there is less actual material available to bear the load. This reduces the load-bearing capacity of the material, resulting in a lower maximum tensile or compressive strength. Porosity can serve as initiation sites for cracks. When the material is subjected to mechanical loads, cracks may start at or propagate from these voids. This can significantly reduce the material's ability to withstand stress. Porosity can also negatively affect the bonding between the reinforcing fibers and the polymer matrix. Porosity can create stress concentrations, which can lead to local material failure. These stress concentrations can exacerbate the effects of applied loads and lead to earlier material failure.

Table 3. Summary of the tensile testing results.

Specimen Type	# of Specimens Tested	Attenuation difference	Max Tensile Strength	Recovery Rate
Specimen-1	1	8	312.37	60.0
Specimen-2	1	8	314.78	60.3
Specimen-3	1	8.2	311.53	59.9
Specimen-4	1	14	288.02	55.28
Specimen-5	1	16	264.77	50.76
Specimen-6	1	16	235.17	45.22
Intact	1	4	520.34	-
Prepreg Specimen Mean	6	12.53	287.77	55.32

It is crucial to highlight that relying solely on decibel differences can be misleading when performing engineering assessments. Attenuation differences, although expressed in decibels, represent more than just numerical values. They signify the intricate interplay of various factors influencing the structural behavior, such as bonding quality, cohesive failure, and porosity. Therefore, a holistic engineering evaluation should take into account not only the numerical values but also the underlying mechanisms that drive these differences.

5. Conclusion

In this experimental study, an investigation was conducted into the strength recovery values of prepreg repairs using wet lay-up repair techniques, with a specific focus on stepped repaired CFRP laminates. Three distinct failure mechanisms that contribute to the mechanical response of these repairs were observed. Adhesive failure was observed within the bonded areas for repairs with a 16-decibel attenuation difference. When the attenuation difference was 12 decibels, a mixed response, including both cohesive and adhesive failures, was noted in the bonded area. Conversely, for repairs with a 4-decibel attenuation, structural failure was observed due to adherend failure, with minimal damage in the bonded area. Significantly, the 8-decibel attenuation exhibited a mixed response characterized by a combination of adherend and cohesive failures. The study aimed to assess the effects of on-site repair scenarios. Initially, a 60% strength recovery was observed for repairs with an 8-decibel difference. However, as the decibel difference increased, the strength recovery gradually decreased, ultimately reaching 39%. This research sheds light on the critical factors influencing the strength recovery of prepreg repairs and provides valuable insights into the significance of adhesive selection, attenuation differences, and failure mechanisms in the context of on-site repair scenarios. The essential factors that affect repair strength have been experimentally established in the study that is being presented, and an experimental framework for improving repair performance in real-world settings has been offered.

It is evident that porosity's impact extends beyond the realm of static strength; it permeates the intricate fabric of a structure's fatigue life. Porosity represents more than just localized voids; it embodies a web of challenges, including stress concentration, crack initiation, and compromised bonding integrity. These challenges, when subjected to the cyclical stresses experienced during the life of an aircraft, contribute to fatigue damage. As such, porosity topics should be evaluated not only in the context of static strength but also in the broader spectrum of fatigue life.

In future studies, porosity analysis can be extended to thicker specimens, where the increase in thickness becomes critical in the secondary bonding of repairs. Investigating the porosity effect in repairs utilizing film adhesive within the matrix of the prepreg can provide valuable insights. Understanding how porosity varies with the increased thickness will be crucial for optimizing the secondary bonding process in thicker repairs.

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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